A DESI DR1 Radial-Velocity Search for Dark Compact Companions:
A Strong but Unconfirmed Candidate Around a dM0 Star

Aiden Smith (A.I Sloperator)

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Abstract

We present a conservative, fully reproducible search for radial-velocity (RV) variability in the public Dark Energy Spectroscopic Instrument (DESI) Data Release 1 (DR1) Milky Way Survey. Using only per-epoch RV measurements, we identify stars whose velocity variability is both highly significant and robust under leave-one-out tests. A "negative space" validation pipeline then rejects ordinary luminous companions using Gaia DR3 astrometry, WISE infrared photometry, GALEX ultraviolet imaging, TESS and ZTF time-domain photometry, deep Legacy Survey imaging, and archival X-ray and radio catalogs.

One system, Gaia DR3 3802130935635096832 (DESI TargetID 39627745210139276), emerges as the most extreme survivor. DESI provides four RV epochs spanning 38.9 days with a maximum RV span $\Delta \mathrm{RV}_{\max} \approx 146\,\mathrm{km\,s^{-1}}$. A constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only), and the variability remains highly significant under leave-one-out tests.

A key forensic update is that Gaia resolves a neighbor at $\rho \simeq 0.69''$ with $\Delta G \simeq 2.21$ mag, implying $\sim 13\%$ flux contamination in G and potentially ~ 10–23% in the DESI R/Z bands. We therefore perform a blend-aware remeasurement of the DESI spectra using two PHOENIX templates and physically motivated flux-ratio priors, and we apply an additional "truth filter" consisting of arm-split RV checks and feature-level RV measurements. The large RV swing persists across these remeasurements, and simple flux dilution from the neighbor cannot produce a spurious $\sim 146\,\mathrm{km\,s^{-1}}$ excursion. However, a persistent R–Z arm discrepancy as large as $\sim 67\,\mathrm{km\,s^{-1}}$ in one epoch indicates wavelength-dependent systematics and/or blending pathology that prevents a definitive dynamical mass claim from public data alone.

LAMOST provides archival spectra that constrain the primary to be an early M dwarf, but independent RV remeasurement of the LAMOST spectra is inconclusive due to internal inconsistencies; we therefore do not use LAMOST RVs to anchor the orbit. We classify Gaia DR3 3802130935635096832 as a *strong but unconfirmed* dark compact companion candidate: the evidence favors genuine high-amplitude RV variability in a system with little corresponding light from a massive companion, but the orbit and dynamical mass remain underdetermined and susceptible to wavelength-dependent systematics. A small number of new high-resolution RV measurements that resolve the blended components would be sufficient to confirm or refute the compact-object interpretation.

1 Introduction

Quiescent compact objects—white dwarfs (WDs), neutron stars (NSs), and stellar-mass black holes (BHs)—are expected to be abundant in the Milky Way but are difficult to detect when not accreting or otherwise luminous. Radial velocities provide a purely gravitational discovery channel: a compact companion can induce large reflex motion in an ordinary star while contributing negligible light. Modern multi-epoch spectroscopic surveys are therefore natural hunting grounds for unseen companions.

DESI DR1 provides per-epoch RVs for millions of stars in the Milky Way Survey. While DESI was not designed as a time-domain survey, the combination of multi-epoch coverage, high spectral resolution, and uniform data processing enables a systematic search for RV outliers. In this work we:

1. define conservative RV-variability metrics that are robust to outliers;
2. scan the DESI DR1 Milky Way Survey for high-significance RV variables;
3. apply a multi-wavelength "negative space" filter that searches for *gravity without light*;
4. perform targeted orbital and forensic analyses of the strongest surviving candidate, including blend-aware remeasurement and wavelength-split stress tests designed to break false positives.

All analysis scripts, configuration files, and machine-readable products are publicly available at `https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH`.

2 Data Sets

2.1 DESI DR1 Milky Way Survey

We use per-epoch DESI DR1 Milky Way Survey RVs from the `main-bright` and `main-dark` programs. For each epoch we extract:

- heliocentric radial velocity RV_i (in $\mathrm{km\,s^{-1}}$);
- formal RV uncertainty $\sigma_{\mathrm{RV},i}$ (in $\mathrm{km\,s^{-1}}$);
- modified Julian date t_i (in days);
- DESI `TARGETID`;
- Gaia DR3 `SOURCE_ID` when available.

2.2 LAMOST archival spectroscopy (typing only; RV treated as uncertain)

We identify two public LAMOST spectra (ObsIDs 437513049 and 870813030) of the target. These spectra robustly support an early-M dwarf classification for the dominant light source. However, independent RV remeasurement of these spectra is internally inconsistent across methods (FITS-header values vs CCF refits and wavelength-split CCF), so we treat LAMOST RVs as *non-decisive* for orbit fitting in this work. We retain LAMOST as the primary spectral-type constraint and as a qualitative sanity check only.

2.3 Gaia DR3 astrometry and duplicity

From Gaia DR3 we use:

- parallax and proper motions;
- renormalized unit weight error (RUWE);

- astrometric excess noise (AEN);
- image-parameter-determination (IPD) summary statistics.

A major forensic update is that Gaia DR3 resolves a close neighbor at a separation $\rho \simeq 0.688''$ with $\Delta G \simeq 2.21$ mag. This neighbor lies within the DESI $1.5''$ fiber aperture and must be treated as a potential blend contaminant.

2.4 Additional surveys

The multi-wavelength validation makes use of:

- WISE/2MASS photometry for infrared colours;
- GALEX NUV imaging for hot WD signatures;
- TESS full-frame-image photometry;
- ZTF multi-year g, r photometry;
- Legacy Survey (DECaLS/MzLS/BASS) imaging cutouts;
- ROSAT, XMM-Newton, Chandra X-ray catalogs;
- NVSS, FIRST, and VLASS radio surveys.

All cross-matching and archive queries are scripted and version-controlled.

3 RV Variability Metrics

3.1 Single-target RV statistics

For each target with N RV epochs we define the maximum observed RV span

$$\Delta \mathrm{RV}_{\max} = \max_i \left(\mathrm{RV}_i\right) - \min_i \left(\mathrm{RV}_i\right). \tag{1}$$

Table 1: Definitions for Equation (1).

Symbol	Meaning
RV_i	Radial velocity at epoch i (in $\mathrm{km\,s^{-1}}$)
$\Delta\mathrm{RV}_{\max}$	Max difference between any two epoch RVs (in $\mathrm{km\,s^{-1}}$)
$\max_i(\cdot)$, $\min_i(\cdot)$	Maximum and minimum over epochs i

To quantify the significance of the variability we define

$$S = \frac{\Delta \mathrm{RV}_{\max}}{\sqrt{\sum_{i=1}^{N} \sigma_{\mathrm{RV},i}^2}}. \tag{2}$$

Table 2: Definitions for Equation (2).

Symbol	Meaning
S	Global RV-variability significance (dimensionless)
$\Delta\mathrm{RV}_{\max}$	As in Equation (1)
$\sigma_{\mathrm{RV},i}$	Formal RV uncertainty at epoch i (in $\mathrm{km\,s^{-1}}$)
N	Number of RV epochs used in the sum

3.2 Leave-one-out robustness and leverage

We compute a leave-one-out significance $S^{(-k)}$ by excluding epoch k and recomputing Equation (2). We then define

$$S_{\mathrm{min,LOO}} = \min_{1\le k\le N} S^{(-k)}, \qquad S_{\mathrm{robust}} = \min\left(S,\, S_{\mathrm{min,LOO}}\right). \tag{3}$$

Table 3: Definitions for Equation (3).

Symbol	Meaning
$S^{(-k)}$	Significance recomputed with epoch k removed
$S_{\mathrm{min,LOO}}$	Minimum of $S^{(-k)}$ over all k
S_{robust}	Conservative RV significance used for selection
N	Total number of epochs for the target

We also define a leverage statistic

$$d_i = \frac{\left|\mathrm{RV}_i - \overline{\mathrm{RV}}\right|}{\sigma_{\mathrm{RV},i}}, \qquad d_{\max} = \max_i d_i, \tag{4}$$

with $\overline{\mathrm{RV}}$ the inverse-variance-weighted mean velocity.

Table 4: Definitions for Equation (4).

Symbol	Meaning
d_i	Leverage of epoch i (number of σ from the mean)
$d_{\max}$	Maximum leverage across all epochs
$\overline{\mathrm{RV}}$	Weighted mean RV of all epochs (in $\mathrm{km\,s^{-1}}$)
$\sigma_{\mathrm{RV},i}$	RV uncertainty at epoch i (in $\mathrm{km\,s^{-1}}$)

4 Negative-space validation pipeline

For each RV-variable candidate we apply a multi-wavelength filter designed to select systems with strong gravitational evidence for a companion but little or no corresponding light from that companion. The key checks are:

1. **Gaia astrometry and duplicity:** RUWE, AEN, and IPD statistics, plus explicit neighbor searches for Gaia-resolved companions.

2. **WISE infrared colours:** $W1 - W2 < 0.1$ to exclude strong IR-excess systems dominated by cool luminous companions.

3. **GALEX NUV:** non-detection to exclude hot WD signatures.

4. **TESS and ZTF photometry:** no deep eclipses, no large-amplitude ellipsoidal modulation, and no strong rotation signal at the candidate orbital period family.

5. **Legacy Survey imaging:** PSF morphology and residuals to identify blends and background contaminants.

6. **X-ray and radio catalogs:** search for accreting NS/BH signatures; non-detections are converted into luminosity upper limits.

Only one object, Gaia DR3 3802130935635096832, survives all cuts and is subjected to the detailed analysis below.

5 Gaia DR3 3802130935635096832

5.1 DESI radial-velocity data set

Table 5 lists the DESI DR1 per-epoch RV measurements.

Table 5: DESI DR1 per-epoch RV measurements for Gaia DR3 3802130935635096832.

Epoch	Source	MJD	Date (UT)	RV $\pm\sigma_{\rm RV}$ ($\mathrm{km\,s^{-1}}$)
1	DESI	59568.488	2021-12-20	-86.39 ± 0.55
2	DESI	59605.380	2022-01-26	$+59.68 \pm 0.83$
3	DESI	59607.374	2022-01-28	$+26.43 \pm 1.06$
4	DESI	59607.389	2022-01-28	$+25.16 \pm 1.11$

The maximum DESI-only RV span is $\Delta\mathrm{RV}_{\max} = 146.07\,\mathrm{km\,s^{-1}}$ over 38.9 days. Applying Equations (2)–(4) yields:

- $S \approx 79.8$ (DESI-only);
- $S_{\min,\mathrm{LOO}} \approx 19.8$ (DESI-only);
- $S_{\mathrm{robust}} \approx 19.8$ (DESI-only);
- $d_{\max} \approx 113$ (high-leverage epoch at -86.39 $\mathrm{km\,s^{-1}}$).

A constant-RV fit to the DESI epochs yields $\chi^2_{\mathrm{const}} \approx 2.73 \times 10^4$ for three degrees of freedom, i.e. a catastrophic rejection of the constant-RV hypothesis.

5.2 Resolved neighbor and blend parameters

Gaia DR3 resolves a neighbor at $\rho \simeq 0.688''$ with $\Delta G \simeq 2.21$. We convert the magnitude difference into a G-band flux ratio

$$b_G = 10^{-0.4\,\Delta G}, \tag{5}$$

which gives $b_G \simeq 0.13$.

Table 6: Definitions for Equation (5).

Symbol	Meaning
b_G	Flux ratio $F_{\rm neighbor}/F_{\rm primary}$ in Gaia G band (dimensionless)
ΔG	Gaia G-band magnitude difference between neighbor and primary (mag)
$F_{\rm neighbor}$	Neighbor flux in G band (arbitrary linear flux units)
$F_{\rm primary}$	Primary flux in G band (same units as $F_{\rm neighbor}$)

Because the DESI fiber diameter is $1.5''$, both sources are plausibly within the fiber. Moreover, the flux ratio is wavelength-dependent: PHOENIX-based SED estimates imply a smaller fraction in the DESI R arm and a larger fraction in the DESI Z arm, with representative values $b_R \sim 0.10$ and $b_Z \sim 0.19$–0.23 for late-M neighbors. This motivates a blend-aware remeasurement and explicit arm-split diagnostics.

5.3 Why flux dilution alone cannot create a $146\,\mathrm{km\,s^{-1}}$ swing

If an RV extractor behaved like a linear flux-weighted centroid of two spectra, the measured RV would be bounded by the flux-weighted average. In the small-b limit, the maximum blend-induced bias scales approximately as

$$|\Delta\mathrm{RV}_{\rm blend}| \lesssim b\,|\mathrm{RV}_2 - \mathrm{RV}_1|\,, \tag{6}$$

so that even a large component velocity separation of $|\mathrm{RV}_2 - \mathrm{RV}_1| \sim 200\,\mathrm{km\,s^{-1}}$ would imply $|\Delta\mathrm{RV}_{\rm blend}| \sim 26\,\mathrm{km\,s^{-1}}$ for $b \simeq 0.13$.

Table 7: Definitions for Equation (6).

Symbol	Meaning
$\Delta\mathrm{RV}_{\rm blend}$	Blend-induced shift in the measured RV (in $\mathrm{km\,s^{-1}}$)
b	Flux ratio F_2/F_1 in the relevant band (dimensionless)
RV_1	True RV of the primary component (in $\mathrm{km\,s^{-1}}$)
RV_2	True RV of the neighbor component (in $\mathrm{km\,s^{-1}}$)
$\lvert\cdot\rvert$	Absolute value operator

This bound does *not* rule out more pathological failure modes (e.g. a pipeline locking onto different spectral components at different epochs, or wavelength-dependent template mismatch), so we explicitly test those cases below using a blend-aware remeasurement and arm-split truth filters.

6 Forensic truth filtering: blend-aware remeasurement and arm/feature checks

6.1 Blend-aware DESI remeasurement

We re-fit the DESI spectra using PHOENIX templates for an early-M primary and a late-M neighbor, performing χ^2 minimization with inverse-variance weights and a physically motivated prior on the flux ratio informed by ΔG and SED-based b_R, b_Z expectations. Across reasonable choices of primary/neighbor templates and fixed blend fractions ($b \in \{0.05, 0.13, 0.20\}$), the inferred combined-arm RV swing remains $\sim 142\,\mathrm{km\,s^{-1}}$, consistent with the catalog swing. This indicates that the large RV excursion is not an obvious artifact of neglecting a $\sim 13\%$ contaminant.

However, model-comparison statistics (e.g. ΔBIC) strongly prefer two-component fits even when b is fixed to unrealistically small values. Because the reduced chi-squared values remain $\chi^2_\nu \gg 1$ in many fits, we interpret these ΔBIC preferences as being driven primarily by template mismatch (i.e. model misspecification), not as decisive evidence that the blend explains the RV variability.

6.2 Arm-split consistency and the epoch-3 anomaly

As an internal consistency check we estimate RVs separately in the DESI R and Z arms. We define an arm-split diagnostic

$$\delta_{RZ} = \mathrm{RV}_R - \mathrm{RV}_Z, \tag{7}$$

where RV_R and RV_Z are the arm-specific RV estimates.

Table 8: Definitions for Equation (7).

Symbol	Meaning
δ_{RZ}	RV difference between DESI R and Z arms (in $\mathrm{km\,s^{-1}}$)
RV_R	RV measured from the DESI R arm (in $\mathrm{km\,s^{-1}}$)
RV_Z	RV measured from the DESI Z arm (in $\mathrm{km\,s^{-1}}$)

We find that one epoch exhibits a large and persistent discrepancy, $|\delta_{RZ}| \sim 67\,\mathrm{km\,s^{-1}}$, which remains after testing alternative masks (including TiO-focused masks). This behavior is consistent with wavelength-dependent systematics and/or differential blending between arms (notably since $b_Z > b_R$ is expected for late-M neighbors). This arm-split pathology is a primary reason we classify the candidate as *strong but unconfirmed* based on public data alone.

6.3 Feature-level RV checks

We perform a feature-level RV sanity check by measuring shifts in prominent molecular/atomic regions (e.g. TiO and the Ca II triplet). These checks recover a large inter-epoch velocity shift of order $\sim 100\,\mathrm{km\,s^{-1}}$ between the most extreme epochs, qualitatively consistent with the catalog-scale variability and inconsistent with the idea that the entire swing is a pure pipeline artifact. However, the feature-level results vary by band/feature and are therefore treated as corroborating diagnostics rather than definitive RVs.

7 Primary-star characterization

Using LAMOST spectral typing and photometry we estimate:

- effective temperature $T_{\mathrm{eff}} \simeq 3850$–$4050$ K;
- surface gravity $\log g \simeq 4.5$;
- metallicity consistent with solar within ± 0.3 dex;

- stellar mass $M_1 \approx 0.56 \pm 0.06$ M$_\odot$;
- radius $R_1 \approx 0.56 \pm 0.05$ R$_\odot$.

Because the system is a known blend at the $\sim$ 10–20% level (band-dependent), these stellar parameters should be regarded as referring to the dominant-light component and may carry additional systematic uncertainty.

8 Dynamical interpretation (conservative bounds)

With sparse sampling and arm-dependent systematics, we do not claim a unique orbital period or a definitive mass posterior from public data alone. We instead provide conservative bounds to illustrate the regime implied by the observed RV span.

The DESI-only RV span implies a minimum semi-amplitude

$$K_{\min} = \frac{\Delta \mathrm{RV}_{\max}}{2}, \tag{8}$$

so that $K_{\min} \approx 73\,\mathrm{km\,s^{-1}}$.

Table 9: Definitions for Equation (8).

Symbol	Meaning
$K_{\min}$	Minimum possible RV semi-amplitude consistent with the observed span (in $\mathrm{km\,s^{-1}}$)
$\Delta\mathrm{RV}_{\max}$	As in Equation (1)

Assuming a circular orbit and adopting $K = K_{\min}$, the mass function is bounded by

$$f_{\min}(M) = \frac{P\,K_{\min}^3}{2\pi G}, \tag{9}$$

where P is the orbital period and G is Newton's gravitational constant.

Table 10: Definitions for Equation (9).

Symbol	Meaning
$f_{\min}(M)$	Minimum RV mass function implied by $K_{\min}$ (in M$_\odot$ when converted)
P	Orbital period (days or seconds, with unit conversion)
$K_{\min}$	As in Equation (8) (in $\mathrm{km\,s^{-1}}$)
G	Gravitational constant (in $\mathrm{m^3\,kg^{-1}\,s^{-2}}$)
π	Mathematical constant pi (dimensionless)

For illustrative periods of order tens of days, $f_{\min}(M)$ is of order unity, implying that a NS-mass companion is plausible for edge-on geometries. Importantly, if the sampling did not capture the true extrema, then $K > K_{\min}$ and the implied mass function increases rapidly as K^3.

9 Photometric, X-ray, and radio constraints

9.1 TESS and ZTF photometry

TESS full-frame data show no deep eclipses or large coherent modulation at the candidate period family. ZTF g, r light curves show amplitudes below ~ 25 mmag at representative periods, disfavoring starspot-driven RV signals at the $\sim 70\,\mathrm{km\,s^{-1}}$ level.

9.2 X-ray and radio upper limits

No counterparts are found in major X-ray or radio catalogs at useful depths. These non-detections are consistent with a detached system containing a non-interacting compact object, but are not uniquely diagnostic.

10 Limitations

Several limitations prevent a definitive claim:

1. **Sparse RV sampling.** DESI provides four epochs (two nearly simultaneous). This is sufficient to prove strong variability but not to uniquely determine the orbit.
2. **Resolved neighbor / blending.** A Gaia-resolved neighbor at $\rho \simeq 0.69''$ contaminates the DESI fiber. While flux dilution alone cannot generate the full RV swing, wavelength-dependent blending and pipeline/template systematics remain plausible contributors.
3. **Arm-dependent systematics.** A persistent R–Z discrepancy up to $\sim 67\,\mathrm{km\,s^{-1}}$ in one epoch indicates a wavelength-dependent pathology that must be resolved before claiming a dynamical mass.
4. **LAMOST RV instability.** LAMOST spectra support the dM0 typing, but independent RV confirmation from LAMOST is inconclusive due to internal inconsistencies.

11 Conclusions and follow-up priorities

We have built and stress-tested a public, scripted pipeline for identifying RV variables with unseen companions in DESI DR1. Gaia DR3 3802130935635096832 is an extreme DESI RV variable with $\Delta\mathrm{RV}_{\mathrm{max}} \approx 146\,\mathrm{km\,s^{-1}}$ and a strong "darkness" profile (no strong IR/UV excess, no large-amplitude optical variability, and no X-ray/radio detection). A Gaia-resolved neighbor at $\rho \simeq 0.69''$ is real and must be accounted for; blend-aware DESI remeasurement shows that the large RV swing persists and cannot be trivially attributed to a $\sim 13\%$ contaminant. However, a large and persistent arm-split discrepancy demonstrates that wavelength-dependent systematics remain a serious obstacle.

We therefore classify Gaia DR3 3802130935635096832 as a *strong but unconfirmed* dark compact companion candidate. The most efficient next step is high-resolution spectroscopy with spatial and/or spectral discrimination of the two components (or conditions that allow robust two-component RV extraction), supplemented by high-angular-resolution imaging to characterize the neighbor. A modest number of additional RV measurements would either confirm a coherent orbit for the primary or demonstrate that the DESI variability is dominated by blend/pipeline systematics.

Data and code availability

All scripts, configuration files, diagnostic plots, and machine-readable results used in this work are publicly available at:

https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH